WIDEBAND HF NOISE/INTERFERENCE MODELING
PART II: HIGHER ORDER STATISTICS

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This report is the second in a series of reports which describe the development of a wideband HF noise/interference model. The model is based on measured data and is suitable for implementation in a wideband HF channel simulator. The measured data, analyses of the first-order statistics of the data, and a proposed noise/interference model based upon those analyses were discussed in Part I of this series. The present report, Part II of the series, describes analyses of selected higher-order statistics of the data: the autocorrelation function and pulse width and pulse spacing distributions. Examples of these quantities generated from the model are compared with measured data, and refinements of the model based upon analyses of the higher-order statistics are discussed.

Key words: channel simulator; noise/interference; wideband HF

1. INTRODUCTION

1.1 Background

During the past several years interest in HF communication systems over wide bandwidths (on the order of 1 MHz or more) has been revitalized. This resurgence of interest in wideband HF has been motivated by the application of spread spectrum technology to HF systems and the development of digital signal processing techniques which enable the development of HF systems having far better performance than HF systems of only a few years ago.

In view of the numerous uncertainties concerning the performance of new communication systems which have not been fielded and tested extensively, channel simulation is an attractive approach for the evaluation of communication system performance. Channel simulation enables the laboratory performance evaluation of communication systems without the cost and time of building hardware and running extensive field tests. Other advantages of channel simulation, including accuracy, repeatability, stationarity, availability, and parameter variation, have been discussed by Hoffmeyer and Vogler (1987).

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For a number of years, laboratory performance evaluations of narrowband HF communication systems have been conducted using the channel model and channel simulation techniques developed by Watterson et al. Although this narrowband model and its implementation in channel simulators has been widely reported in the literature (Watterson, 1981 and 1982; Watterson and Coon, 1962; Watterson et al., 1962 and 1970; CCIR, 1974; Ehrman et al., 1982; Mooney, 1985; Girault et al., 1988; McRae and Perkins, 1988; LeRoux et al., 1987), the model has only been validated for narrowband (less than 12 kHz) stable channels.

Motivated by the need for a wideband HF channel simulator, the Institute for Telecommunication Sciences has undertaken the development of a wideband HF channel model. The model is to be accurate over wide bandwidths (on the order of 1 MHz or more), validated with measured data, and suitable for implementation in a wideband HF channel simulator. The model is to include noise and interference, which can be quite severe in the HF band, as well as a model of ionospheric skywave propagation.

The wideband propagation model and the implementation of the propagation and noise/interference models in a real-time channel simulator have been discussed elsewhere (Vogler et al., 1988; Vogler and Hoffmeyer, 1988 and 1990; Hoffmeyer and Vogler, 1990; Hoffmeyer et al., 1991; Mastrangelo et al., 1991). The purpose of the present series of reports is to discuss the development of a wideband HF noise/interference model.

1.2 Noise/Interference Model

In Part I of this series (Lemmon and Behm, 1991) a wideband HF noise/interference model based on measured data was presented. It was pointed out that, in contrast to previously developed models which attempt to describe statistical characteristics of the noise/interference, the present model describes the noise/interference waveform itself, which is essential if the model is to be used to simulate that waveform.

The measured data were obtained by the Mitre Corporation as part of its experimental wideband HF communications program. The equipment used in the experiments was described briefly in Part I and in more detail by Perry and Rifkin (1989). The data consist of 42 one-second records of the digitized (sampled at 1.024 MHz), baseband, in-phase (I) and quadrature (Q) components of the received noise/interference over an equivalent rf bandwidth of 800 kHz.

The data were collected in March, 1989 in Bedford, MA at various times of day and at various frequencies in the HF band (3-30 MHz). The times, dates, center frequencies of the data, and the values of the variable attenuation used in the front-end of the receiver are listed in Table A-1 in the Appendix.

To analyze these data, software was developed to generate the following quantities:

- plots of raw data (I and Q)
- probability density function (pdf) of raw data
- pdf of voltage envelope ($\sqrt{(I^2+Q^2)}$)
- pdf of power envelope (I^2+Q^2)
- pdf of phase ($\tan^{-1}Q/I$)
- cumulative distribution function (cdf) of power envelope
- distribution of average level crossing rate of the voltage envelope
- power spectrum
- cdf of power in the frequency domain (sum of the squares of the real and imaginary parts of the complex Fourier transform of the raw data)
- pdf of phase in the frequency domain (phase of the complex Fourier transform of the raw data)

In addition, software was developed to perform the following functions:

- frequency domain excision of narrowband interference
- simulations of noise/interference

Using these analysis tools, a variety of case studies were conducted. Based on the results of the case studies, it was proposed that the noise/interference can be represented as a sum of three components:

- Gaussian noise
- Narrowband interferers (sine waves)

Impulsive noise (filtered delta functions)

The narrowband interference is presumably manmade, arising from numerous users of the HF band. Broadband impulsive noise can be natural (atmospheric noise) or manmade. However, as discussed in Section 3, the impulsive noise analyzed herein is assumed to be of manmade origin, because the time durations of the noise bursts and the times between bursts are not consistent with those of atmospheric noise.

If x(t) denotes the noise/interference signal at rf, and the in-phase and quadrature components of the baseband signal are denoted by I(t) and Q(t), respectively, then x(t) can be written as

$$x(t) = I(t)\cos\omega_0 t + Q(t)\sin\omega_0 t, \tag{1}$$

where ω_0 is the carrier frequency. The proposed noise/interference model describes the complex baseband voltage,

$$z(t) = I(t) + iQ(t), \tag{2}$$

by the expression

$$z(t) = g(t) + \sum_{i=1}^{N_i} A_i e^{-i(\Delta\omega_i t + \phi_i)} + \sum_{j=1}^{N_j} B_j \frac{\sin 2\pi B(t-t_j)}{t-t_j} e^{i\omega_0 t_j}, \tag{3}$$

where g(t) is a complex, zero-mean, white Gaussian process, $\Delta\omega_i$ are the baseband frequencies of the sine waves ($\Delta\omega_i=\omega_i-\omega_0$), ,$\phi_i$ are random phases, B is the bandpass (in Hz) of the low-pass filter in the HF receiver, t_j are the arrival times of the (filtered) impulses, N_i is the number of narrowband interferers in the frequency band of interest, and N_j is the number of impulses in the time interval over which the noise/interference is being modeled. The frequency and phase distributions of the narrowband interferers are uniform, and in Part I the arrival times t_j were also uniformly distributed, although it will be shown in the present report that this is inadequate to correctly model the higher-order statistics.

It remains to specify how the amplitudes A_i and B_j are distributed. In Part I it was proposed that the pdf for the amplitudes A_i be modeled by the amplitude pdf of a model developed by Hall (1966):

$$p(A) = \frac{(\theta_A - 1)\gamma_A^{\theta_A - 1} A}{(A^2 + \gamma_A^2)^{(\theta_A + 1)/2}}, \qquad (4)$$

where θ_A and γ_A are free parameters (with the constraint that $\theta_A > 1$, so that p(A) is normalizable). It was also proposed in Part I that the amplitude distribution of the B_j be described by that of the Hall model for amplitudes which are less than some maximum value B_{max}, and that the distribution be cut off for amplitudes greater than B_{max}:

$$p(B) = \begin{cases} \dfrac{1-\theta_B}{(B_{max}^2 + \gamma_B^2)^{(1-\theta_B)/2} - \gamma_B^{2(1-\theta_B)/2}} \cdot \dfrac{B}{(B^2 + \gamma_B^2)^{(\theta_B+1)/2}}, & 0 \le B \le B_{max} \\ 0, & B > B_{max} \end{cases}, \qquad (5)$$

where θ_B and γ_B are free parameters (with $\theta_B > 1$). The expression in the first line of (5) differs from that in (4) because cutting off the distribution results in a different normalization constant. The techniques used to generate amplitudes distributed according to (4) and (5), and to generate the Gaussian noise, were discussed in Part I.

1.3 Scope

The model described above enables one to simulate noise/interference signals whose statistical characteristics can be compared to those of measured data. Clearly, many such characteristics could be examined. In Part I of this series, the first-order statistics were investigated. These quantities characterize the time-averaged behavior of the noise/interference. It was shown that, for appropriate values of the model parameters, the simulated noise/interference has first-order statistics that closely resemble those of the measured data.

However, a complete characterization of the noise/interference requires investigation of the higher-order statistics as well. These statistics are necessary to specify the relationships between the noise/interference process at different instants in time. For example, it was shown that the average numbers of level crossings of the voltage envelope per unit time of the simulated noise/interference are in agreement with measured data, but it remains to investigate how these envelope crossings are distributed in time.

In this report, selected higher-order statistics of the noise/interference are discussed. To keep the analysis tractable, attention has been restricted to the following three quantities:

- Autocorrelation functions
- Pulse width distributions
- Pulse spacing distributions

Autocorrelation functions are important because they define the time scales over which the noise/interference becomes decorrelated and provide information about the time scales over which the noise/interference processes vary. Pulse width and spacing distributions are useful for detailed modeling of the noise/interference waveforms, especially impulsive noise. These distributions provide information about the fine structure of the noise bursts, as well as information about the nature of the correlations of the noise bursts in time.